

Electron Cloud Instabilities

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Outline

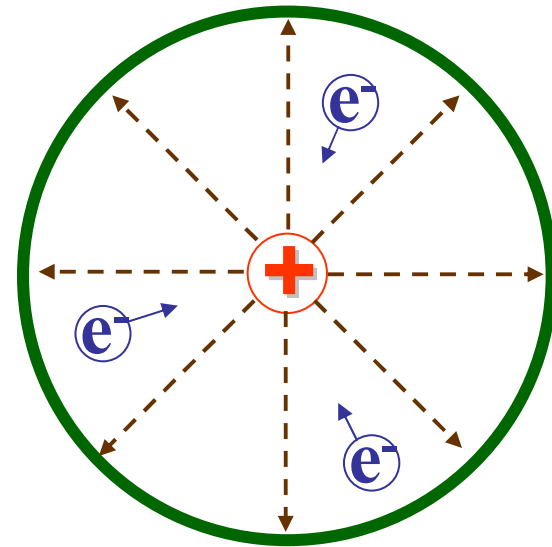
- Electron Cloud Intro
- Formation Process
- Interaction with beam
- Observations at Fermilab

Electron Cloud Basics

- Positively-charged beam
- Produces an electric field
- Supports a persistent plasma of nonrelativistic electrons within the vacuum of the beampipe

Other notes:

- Beam and electrons interact
 - Secondary/photo - emission
 - Primary Production



Why Fermilab Needs to Understand the Cloud

- Fermilab has high-intensity, positive beams
 - However: the cloud does not limit operation of our accelerators ... yet
 - When considering upgrades (intensity increases), we might produce an intense cloud and have to deal with it
 - Proton Plan/Driver - SNuMI
- Fermilab is part of other projects that could likely be limited by the cloud
 - LHC will produce a cloud
 - ILC positron damping ring will produce a cloud
- Almost any higher intensity, positive beam will have to be designed with the electron cloud in mind
 - Performance limitations may be by crippling, or mitigation expensive after the fact

Electron Cloud Research

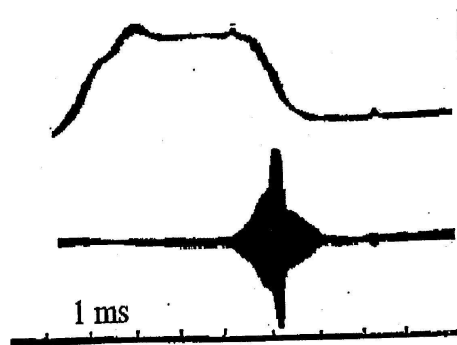
- Study of the cloud split among 3 major topics:
 1. How does the cloud form?
 2. How does the cloud interact with the beam?
 3. How can the cloud be prevented or mitigated?

Whole variety of physical processes and parameters involved

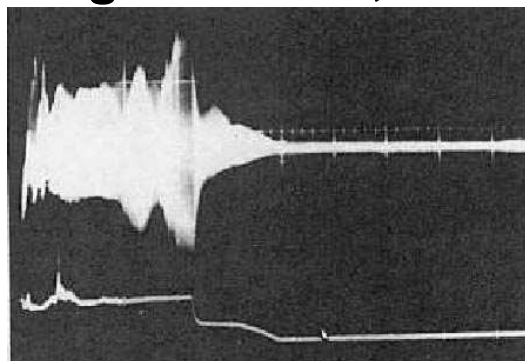
First question: what has been seen so far?

e-cloud beam instabilities at various machines

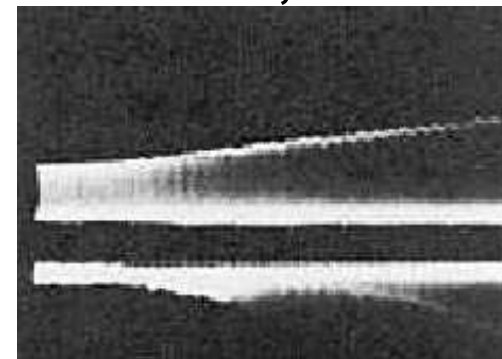
INP Novosibirsk, 1965



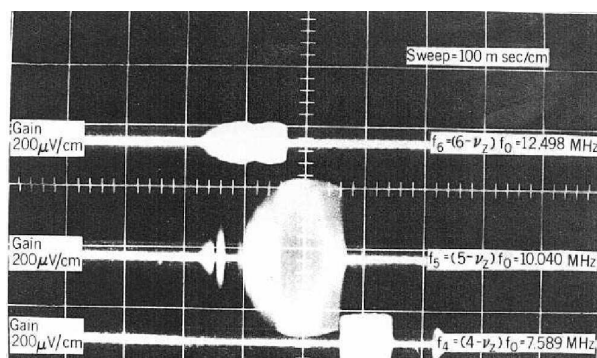
Argonne ZGS, 1965



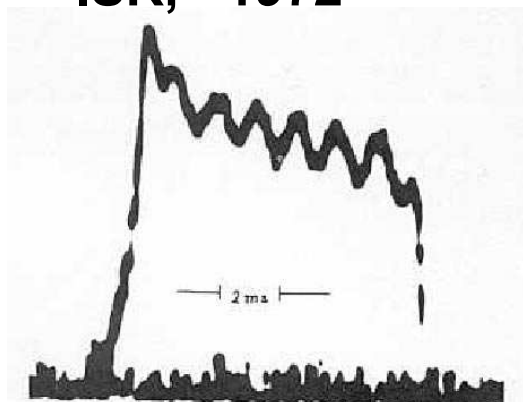
BNL AGS, 1965



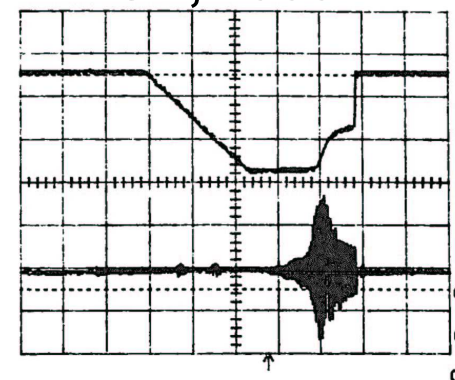
Bevatron, 1971



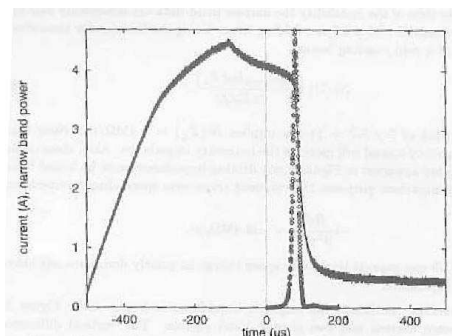
ISR, ~1972



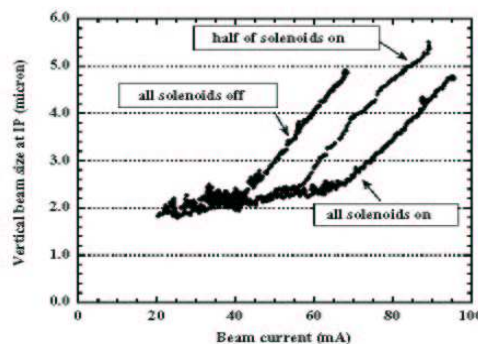
PSR, 1988



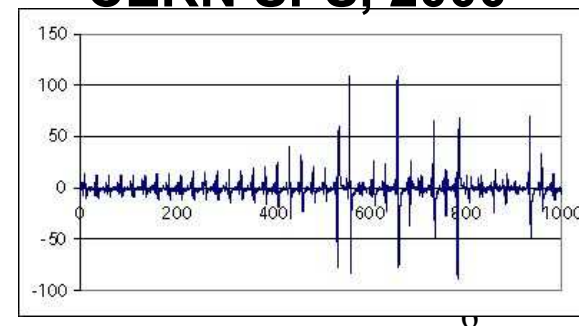
AGS Booster, 1998/99



KEKB, 2000



CERN SPS, 2000



[F.Z. PRST-AB 7, 124801 (2004)]

“critical mass phenomenon”?

hadron machine	$ZN_b/(\sigma_x \sigma_y \sigma_z) [10^8/\text{mm}^3]$
ISR	0.14
CPS	0.28
SPS (LHC)	0.21
SPS (FT)	0.13
PSR	0.15
RHIC	0.10
ISIS	0.006 no e- cloud
SNS	0.30 ←
J-PARC (3 GeV)	0.04 safe?
FNAL 8-GeV PD	0.03 safe?
J-PARC (50 GeV)	0.17 ←
FAIR SIS-18/100	0.23/0.31 ←
LHC	159 ←

e- cloud effects

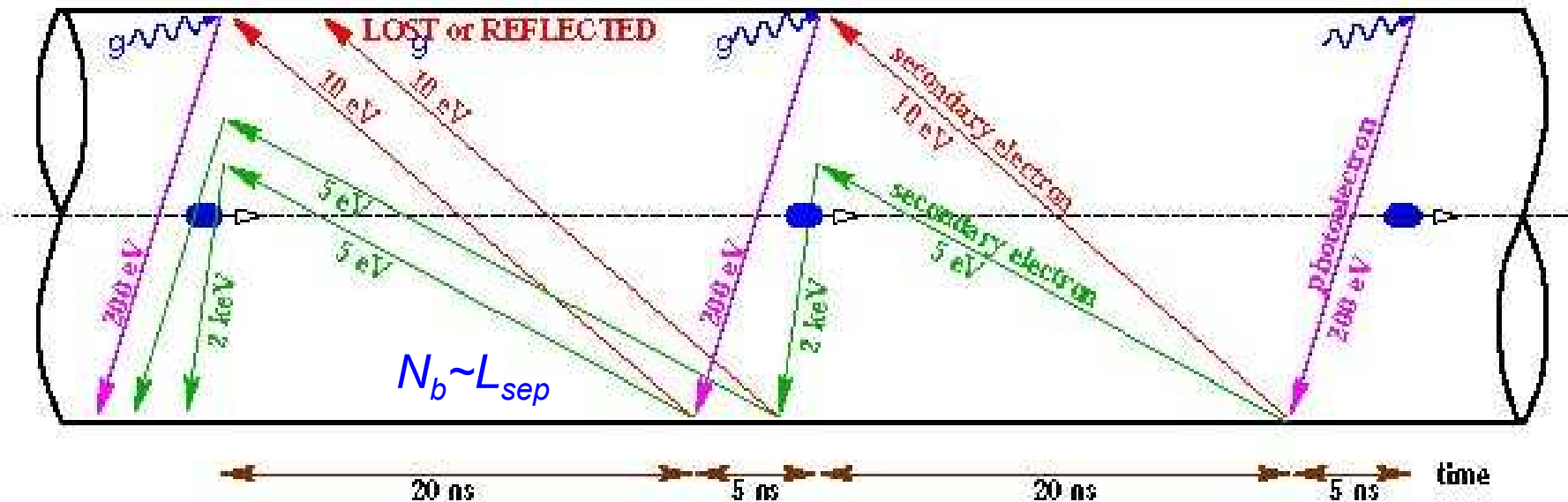
Weiren Chou,
 Oliver Bruning,
 Massimo
 Giovannozzi,
 Elias Metral,
 ECLOUD'02

**planned,
 or under
 construc-
 tion or
 commis-
 sioning**

Different Models of Cloud Formation

- Resonant Production
 - Similar to multipactoring in RF cavities
 - Multiple bunches accelerate electrons at a specific resonance, producing more through secondary emission
 - Assumes an unrealistic number of symmetries
- Photoproduction
 - Huge number of synchrotron photons produce electrons through photo-emission
 - Doesn't require much secondary emission or a cascade
 - Not relevant to proton machines and can be dealt with vacuum antechambers
- Quasi-adiabatic heating
 - Long bunches slowly attract and heat electrons into the center of the beam vessel
 - Expelled at the end of the bunch and produce electrons through secondary emission
- Fast heating – (most relevant to Fermilab)
 - Short bunches shock electrons into the center – heating them
 - Collisions with beam pipe produce a sea of secondary electrons that mill around the walls
 - Subsequent bunches heat the electrons multiple times, producing a cascade
 - Repulsion within a strong cloud can further contribute to heating

electron cloud in the LHC



[Courtesy F. Ruggiero]

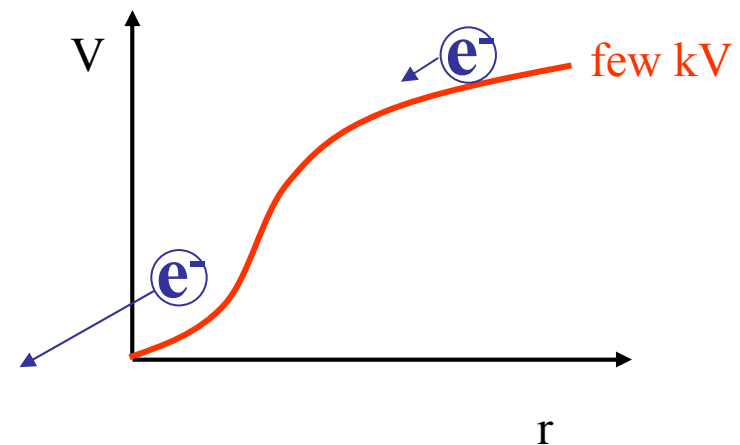
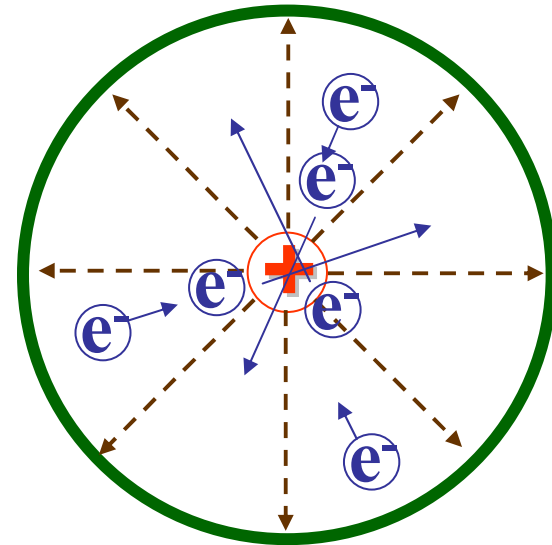
schematic of e- cloud build up in the arc beam pipe,
due to **photoemission** and **secondary emission**

empirical e-cloud threshold scaling: $N_b \sim L_{sep}$

[F.Z., EPAC'02]

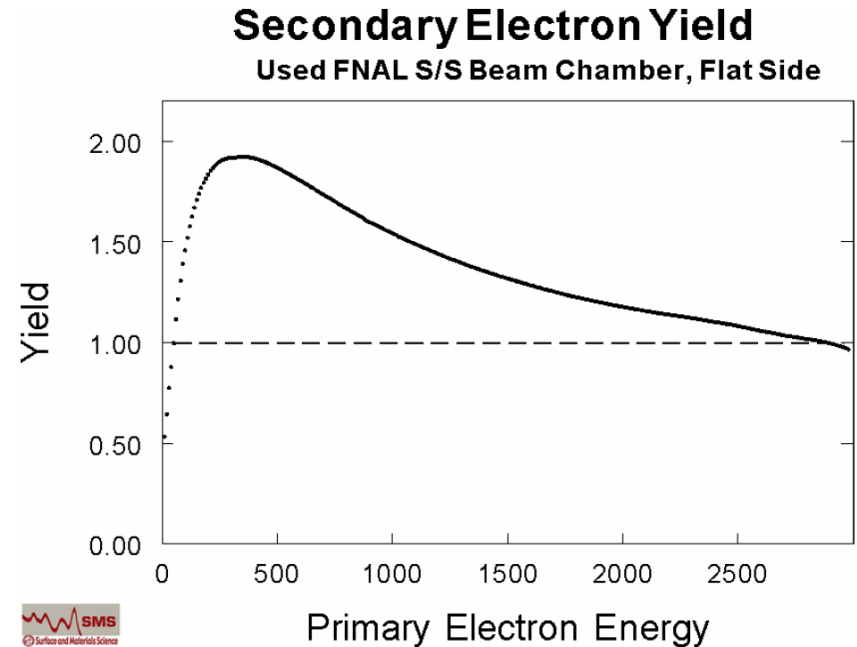
Model at Fermilab

- Considering the MI beam
 - 1-8 ns long bunches every 19 ns
 - 1-5 mm transverse sigma
 - Bunch intensities of 10^{11} protons
- Produce a few initial/primary electrons
 - Residual gas ionization
 - $O(e^- / m / \text{torr} / \text{proton})$
 - Lost protons
 - Can produce 100's in beam pipe
- Beam produces strong potential
 - Nonadiabatic appearance
 - Electrons Accelerate
- Beam disappears
 - Electrons collide with wall



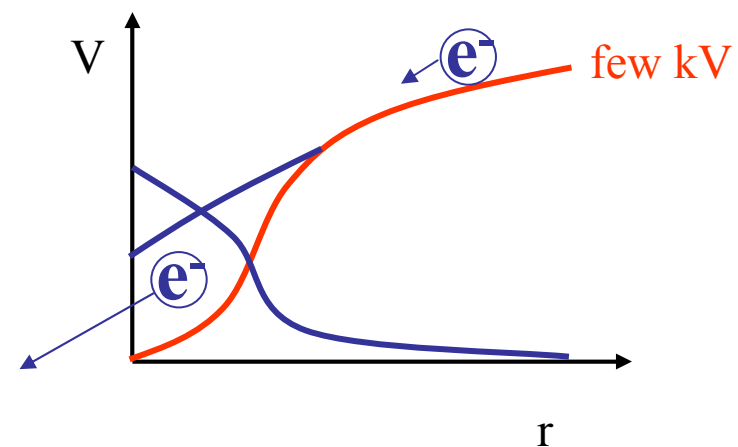
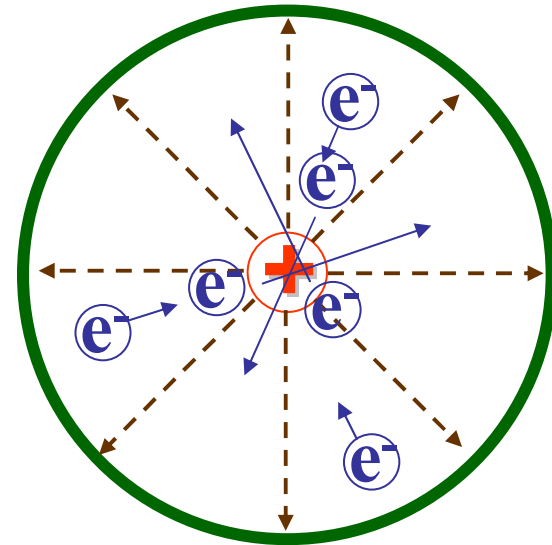
Secondary Emission

- More electrons produced upon collision with wall
 - Conversion of energy to multiplicity
- On average, 2 electrons produced per incident 400 eV electron on MI pipe
- Secondary electron yield (SEY) depends on incident electron's energy
- Different materials and geometries can have different SEYs
- Produced electrons have much lower energies, typically 1-10 eV

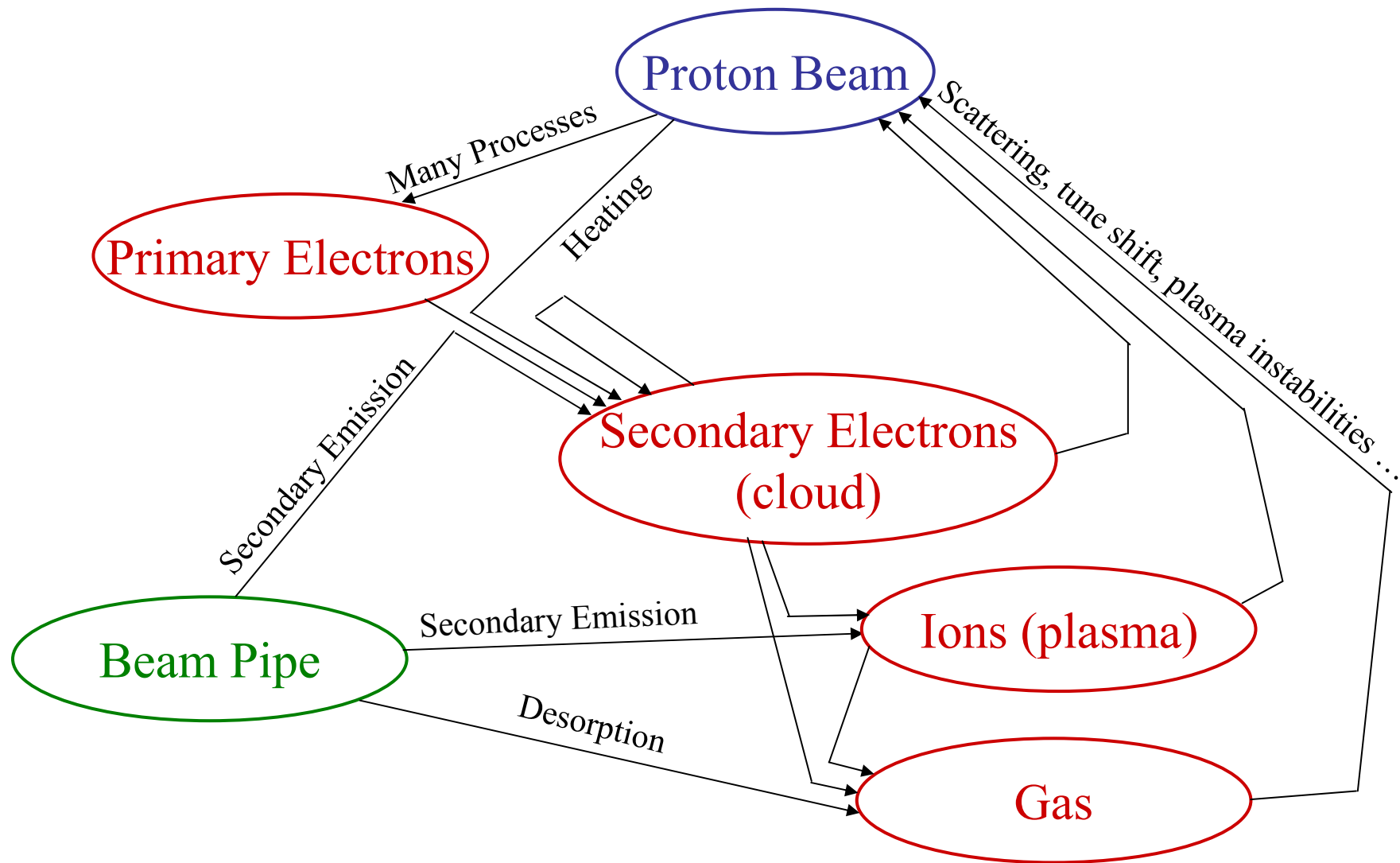


Secondary Electrons Reheated

- Secondaries are reheated in the same way as the primaries
 - Bunches must reappear before secondaries are reabsorbed
 - Potential for exponential growth
- Collective electron charge can increase heating effect
- Eventually, electrons will screen the proton's charge leading to a saturation density
 - Peak electron linear density comparable to peak proton density



Processes Involved



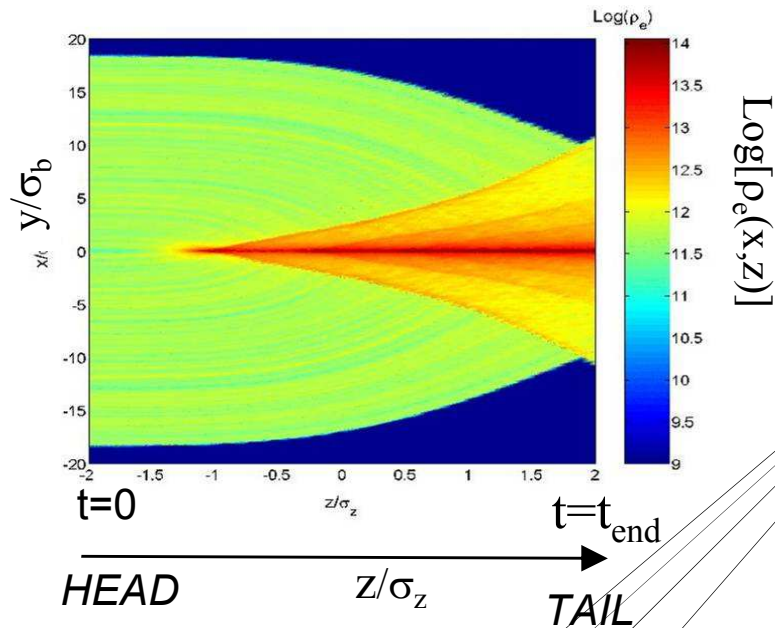
Possible Effects of the Cloud

- Vacuum bursts caused by gas desorption
 - Can activate machine protection
 - Hurt lifetime of storage ring
- New impedance – electrons act as a wake field
- Tune Shifts
 - Normal space charge tune shift can be considered to be the sum of electric and magnetic parts in the lab frame
 - Magnetic partially cancels the electric
 - Electron cloud can neutralize electric, but leave the $F_r = \frac{eI}{2\pi\epsilon_0\beta c}(1 - \beta^2)\frac{r}{a^2}$
 - Tune shift can be potentially large
 - Like a beam-beam effect around the entire ring
 - Potential is also very nonlinear -> emittance growth
 - Also time-varying in bunch and in bunch train

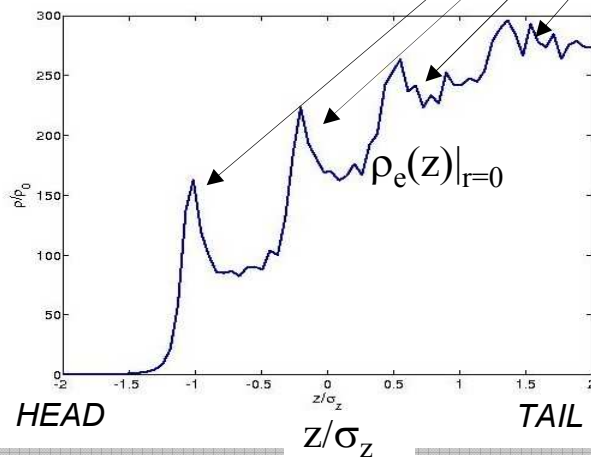


Pinch Model from CERN

Electron cloud evolution



EC density at $(x,y=0,0)$



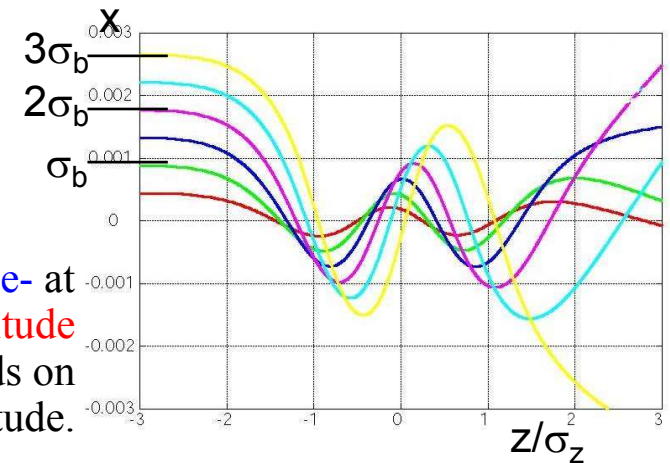
e- motion during the passage of a Gaussian bunch:

– $x < \sim \sigma_x$ harmonic oscillations (~ 4)

$$\omega_e = \sqrt{\lambda_b(z) r_e c^2 / \sigma_r^2} \approx 2\pi \cdot 1.2 \text{ GHz}$$

– $x \gg \sigma_x$ non-linear oscillations

($x > 12\sigma_x$, e- perform less than 1/4 oscillat.)



Position vs. time of e- at different initial amplitude ($0.5, \dots, 3\sigma_b$). ω_e depends on initial amplitude.

→ EC density function of longitudinal position

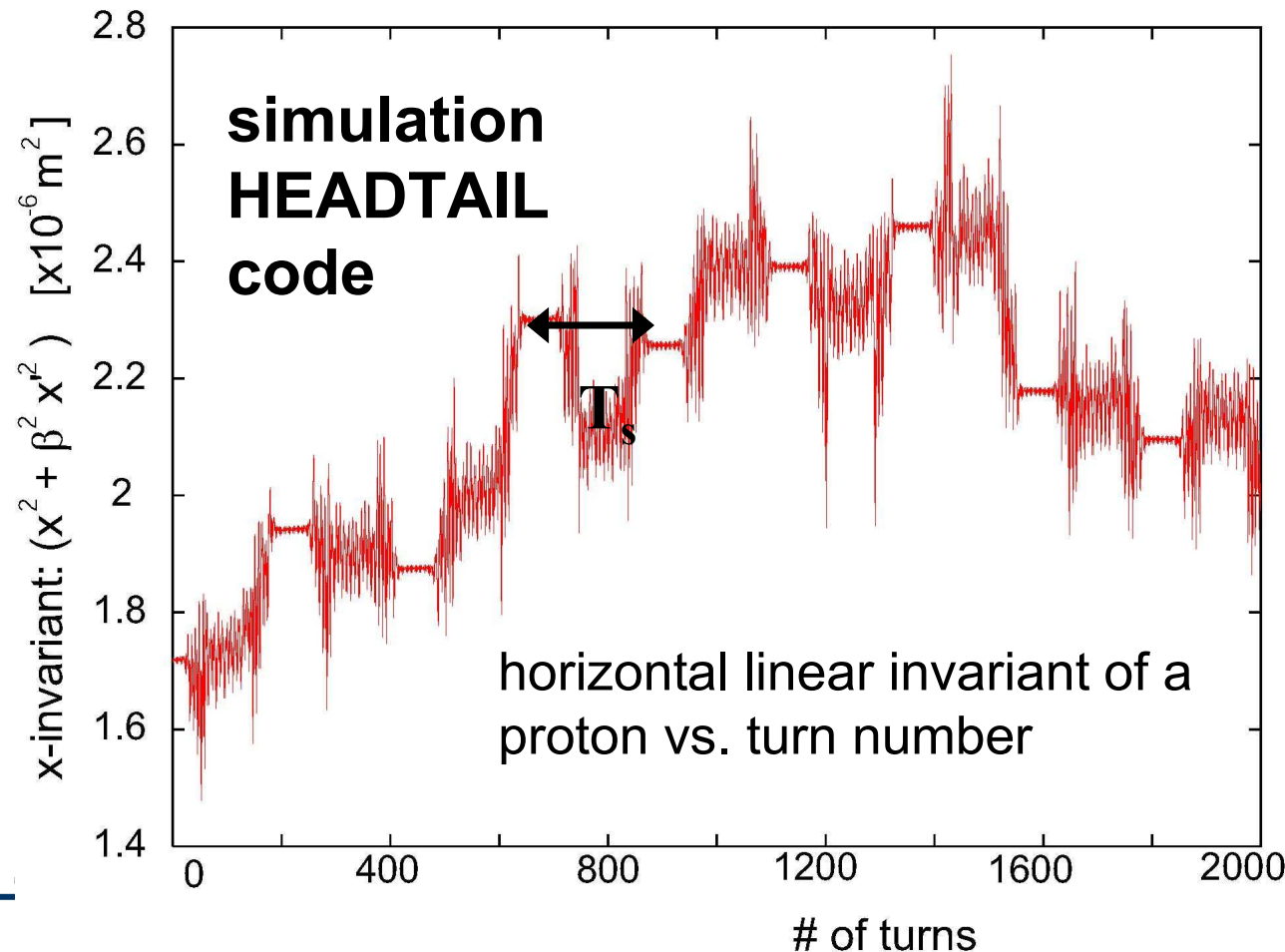


two mechanisms of incoherent e- effect & shrinkage:

✓ periodic resonance crossing → halo growth

✓ periodic linear-instability crossing → core growth

ingredients: (1) synchrotron motion, (2) e- induced tune shift along the bunch (E. Benedetto, G. Franchetti, F. Zimmermann, submitted to PRL)



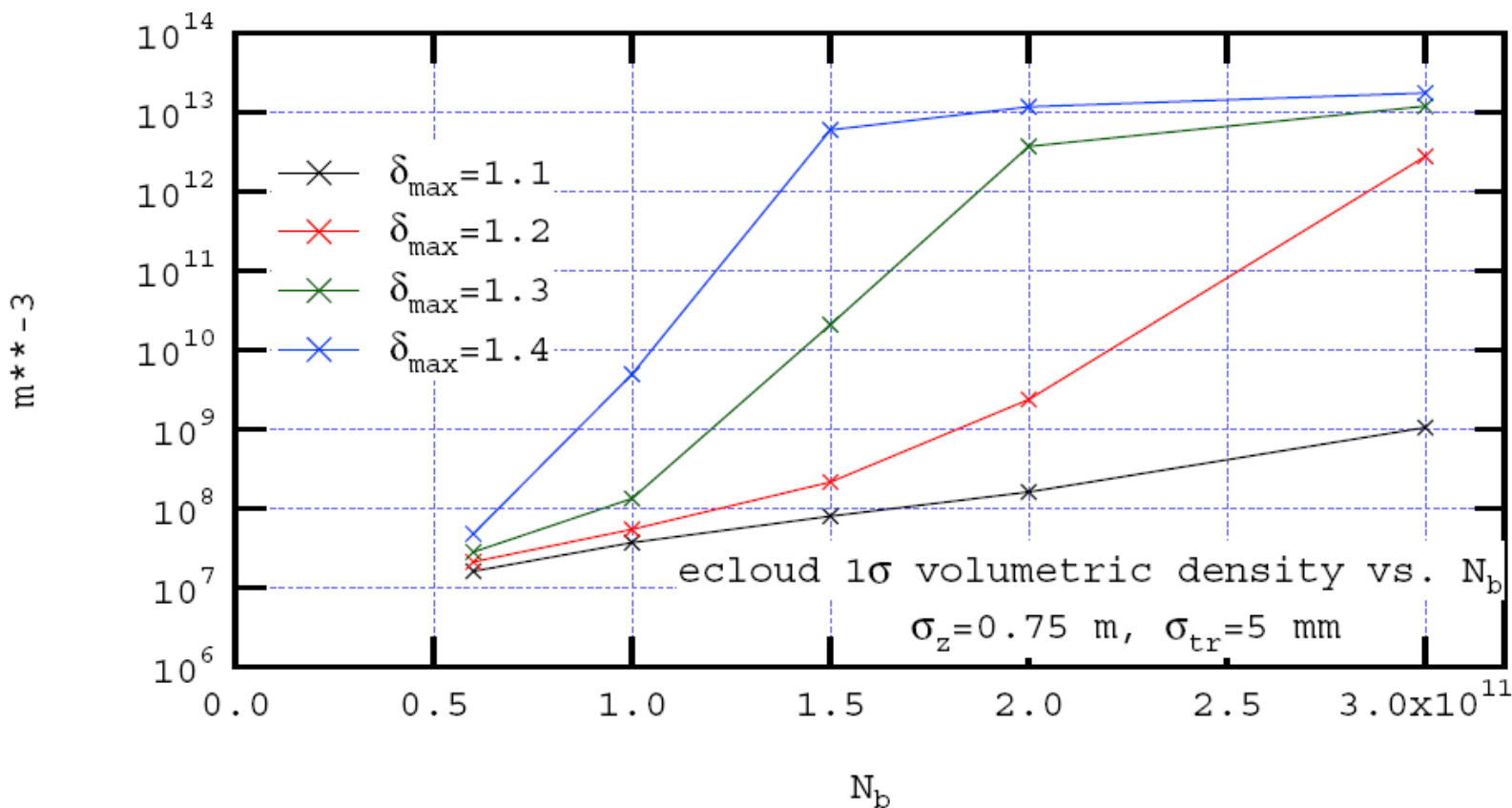
Elena Benedetto &
Giuliano Franchetti

Electron Cloud at MI

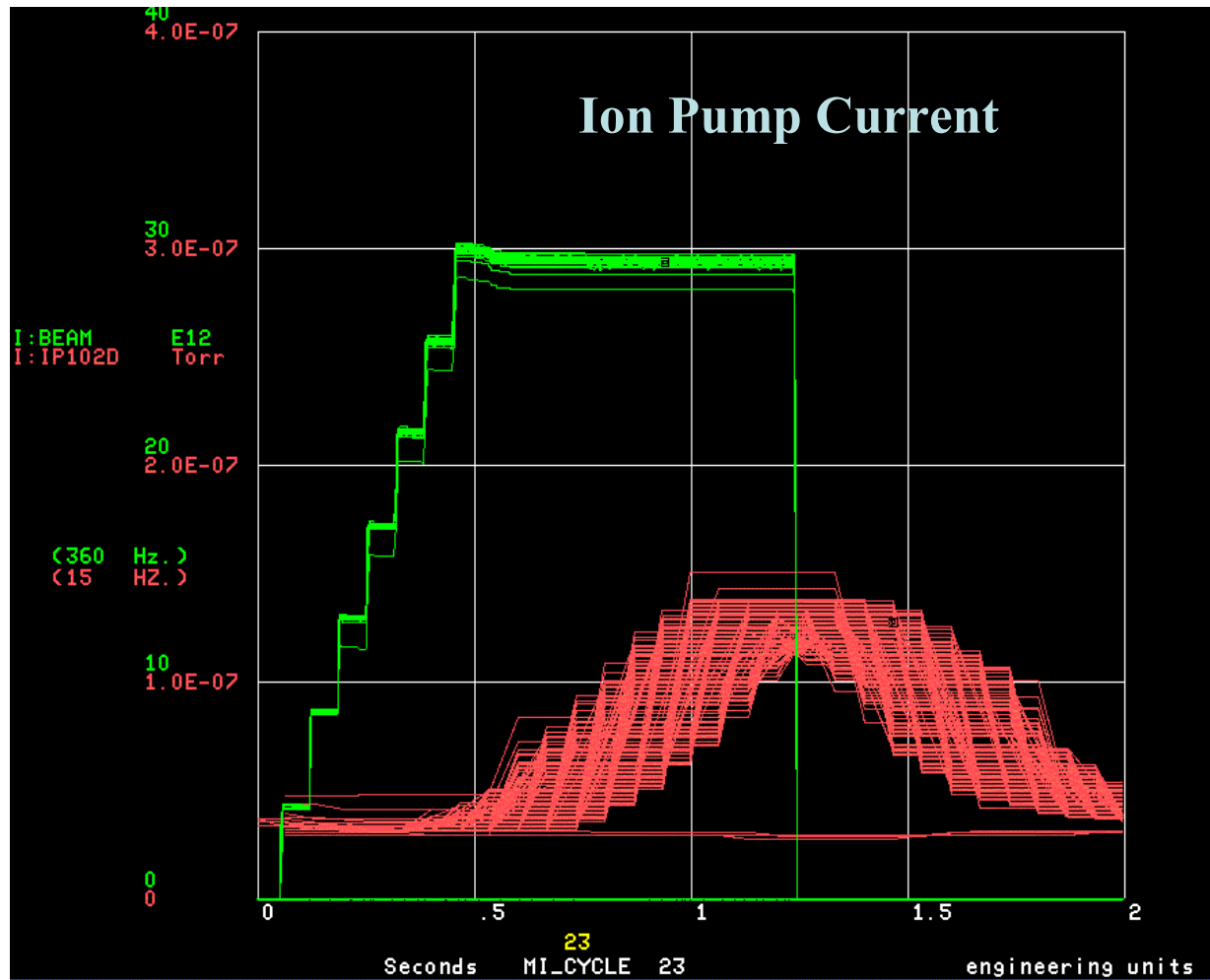
- Currently run with 53 MHz bunches of $6-10 \times 10^{10}$ protons / bunch
 - Question for upgrades: Can the bunch population be brought to 30×10^{10} ?
 - At a review this question was asked for the electron cloud
- Weiren Chou convinced Miguel Furman (LBNL) to simulate electron cloud build-up with POSINST
 - Results prompt further investigation at Fermilab
- Note: the Main Injector does not suffer from the e-p instability
 - However, we can see some evidence of cloud formation
- Intend to study with observations and LBNL simulations

Considering the Cloud

- Simulations suggest that MI might be near a threshold
 - 4-5 orders of magnitude increase of cloud density with a doubling of bunch intensity
- Not yet established:
 - How well code pertains to Main Injector (question of SEY)
 - What the effects of electron neutralization will be on the beam

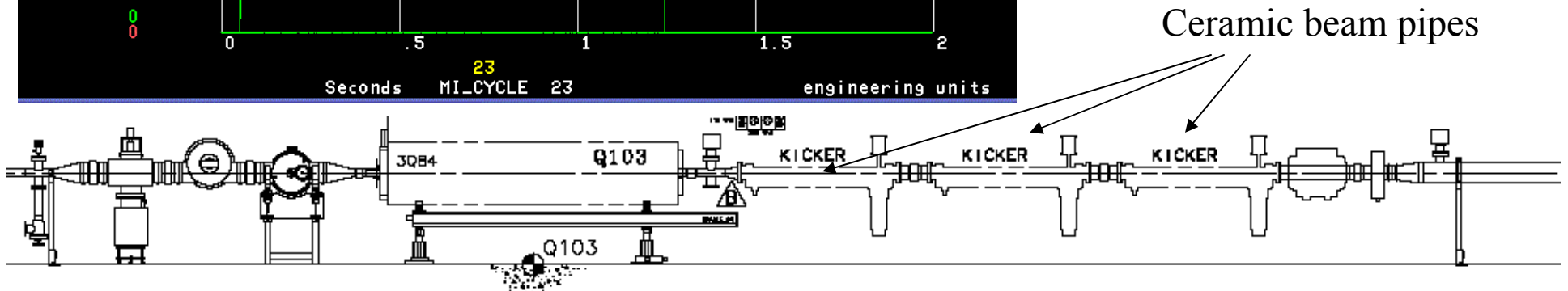


Measurements of Dynamic Pressure Rise

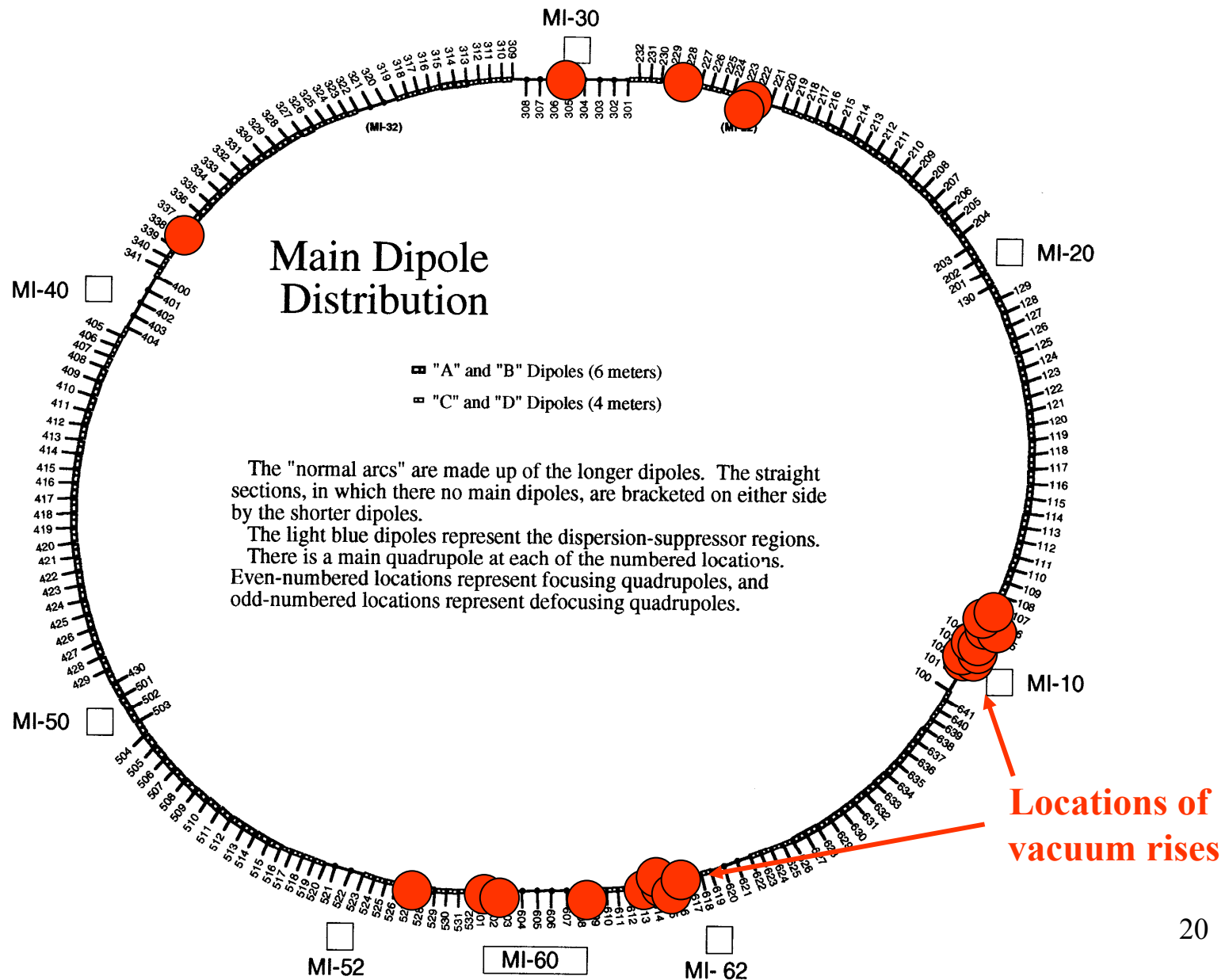


See fast rise over the course of a cycle (1s)

The control system barely keeps up

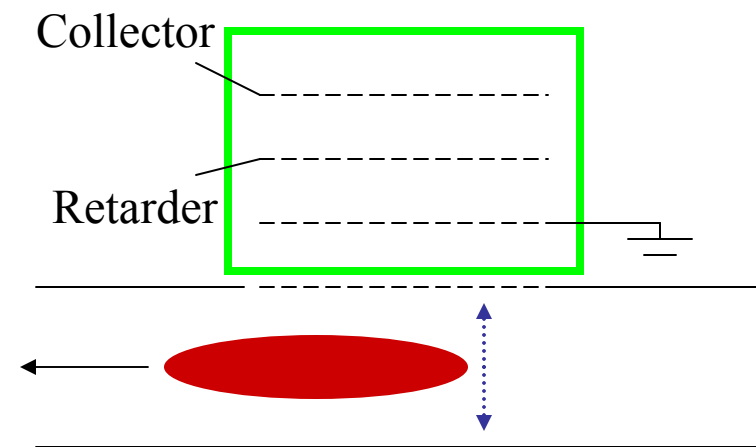
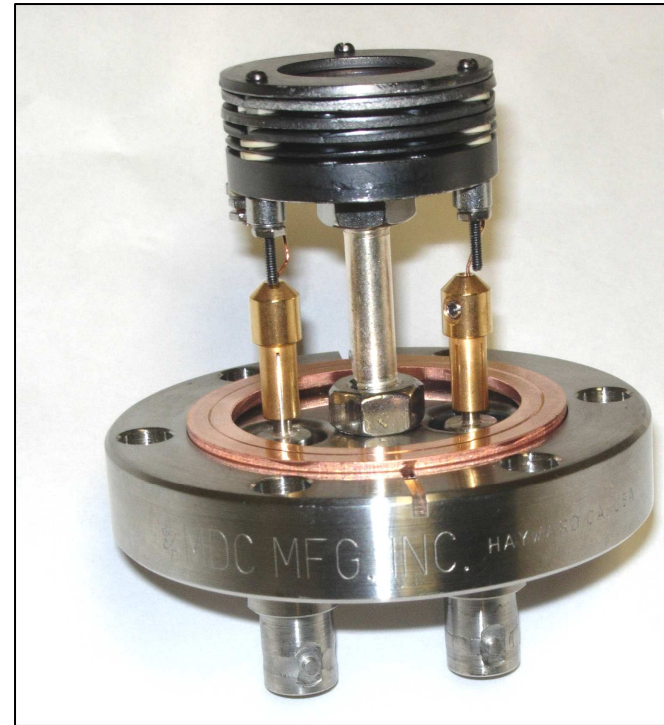


Dynamic Rises Around the Ring



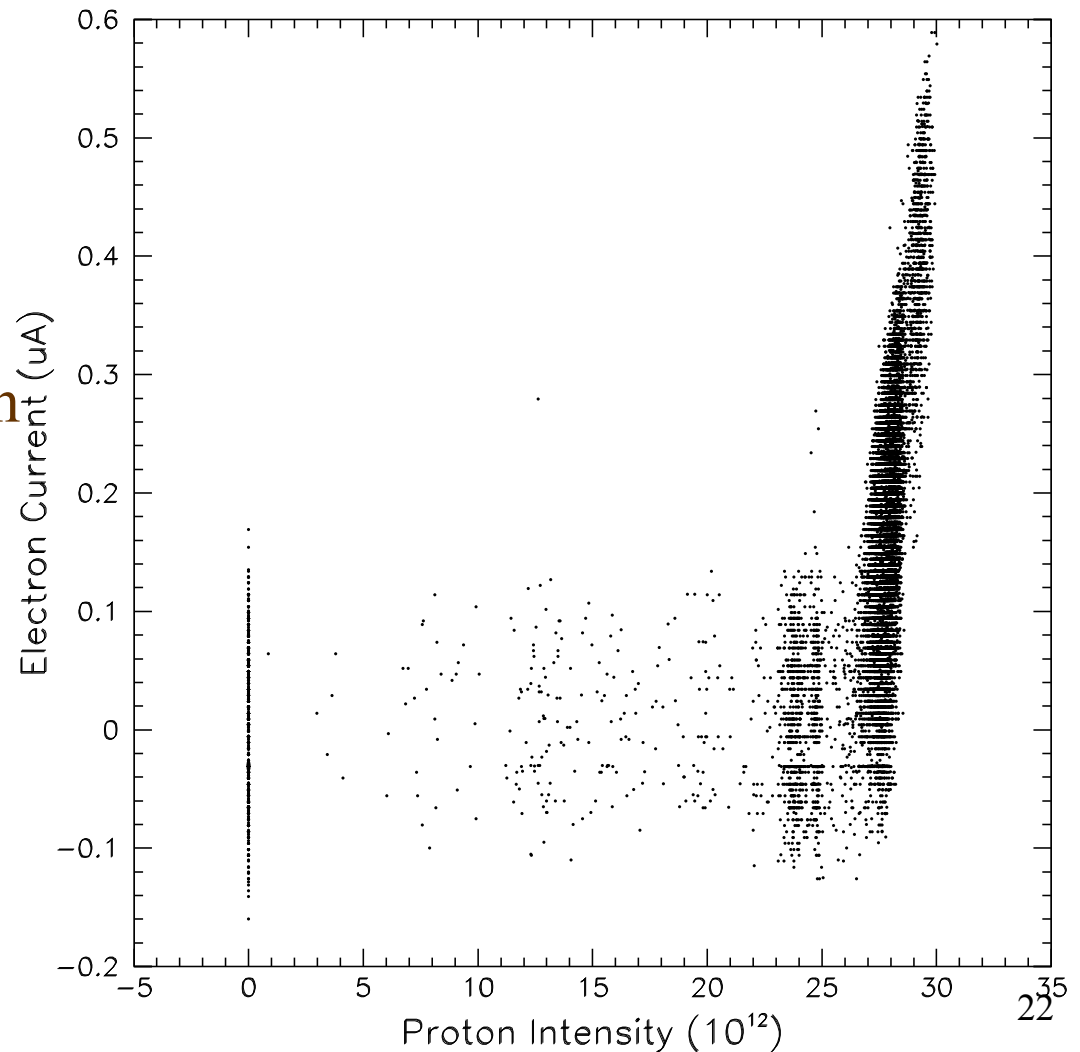
Electron Probe

- “Retarding Field Analyzer”
 - Borrowed from Argonne
- Two electrodes connected externally
 - Retarder can be biased to allow energy measurements
- Currently being used as a simple electron counter
 - Directly measure electron current on the beam pipe

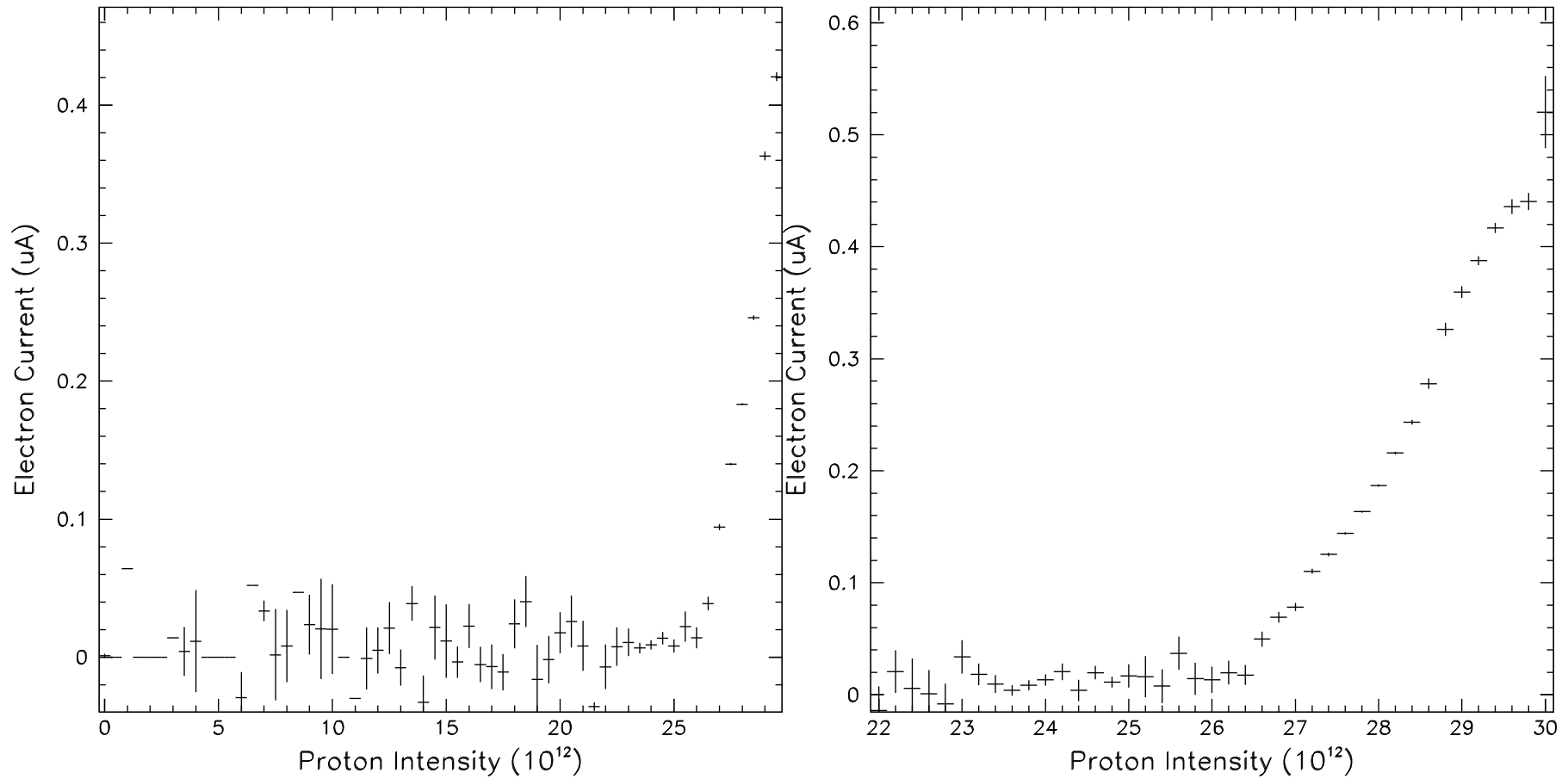


Collected results

- Clear turn-on at higher intensities
- Noise is worse due to amplifier/MADC system
- 0.1 $\mu\text{A} \sim 1\%$ neutralization at 20×10^{12}

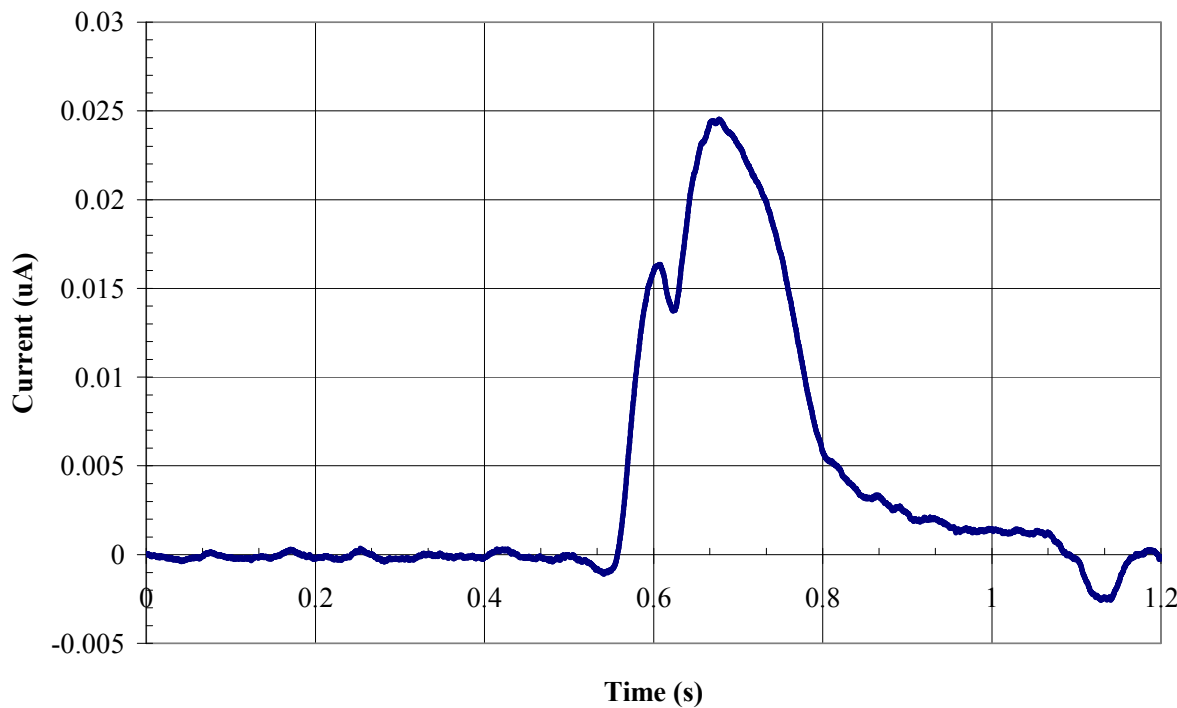


SS+NuMI Histogrammed



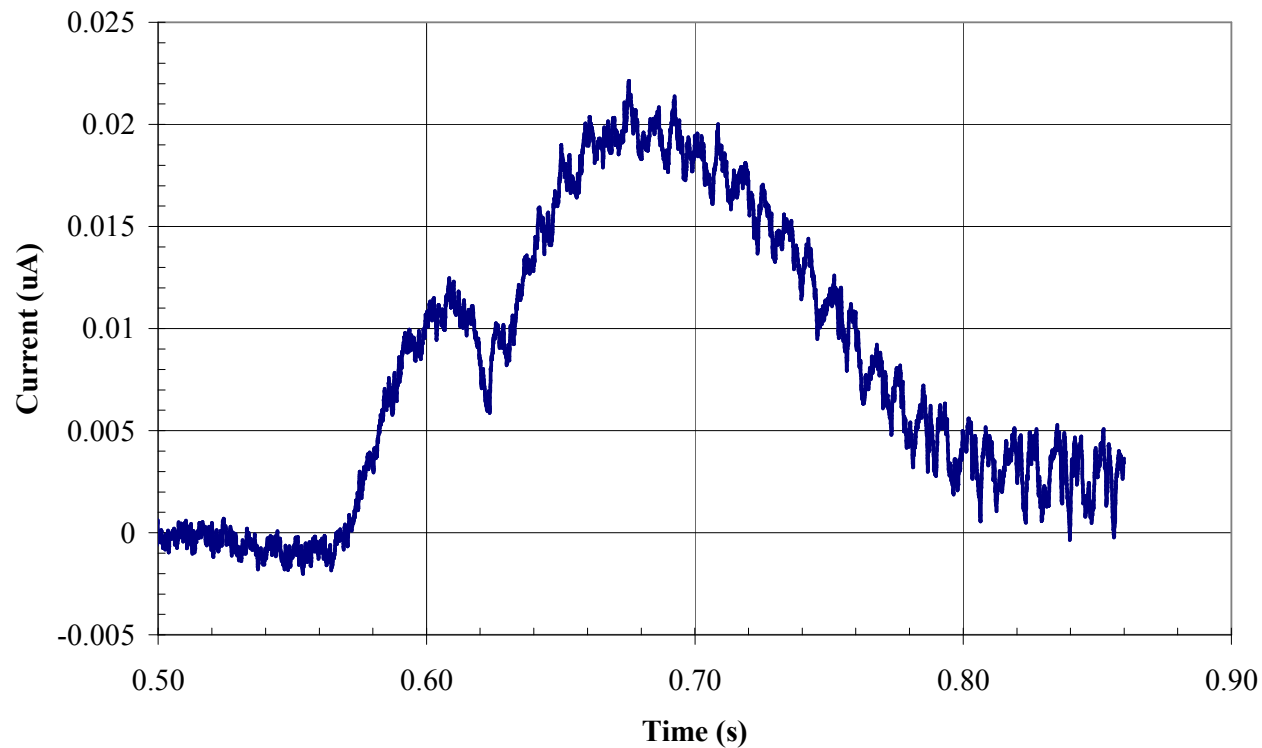
Time Measurements

- Unbiased signal
 - Required lots of noise reduction
 - Could not get a good zero for subtraction
 - Dip at 1.1 s
- Rapid increase of signal occurs into acceleration
 - Dip at transition (next slide)



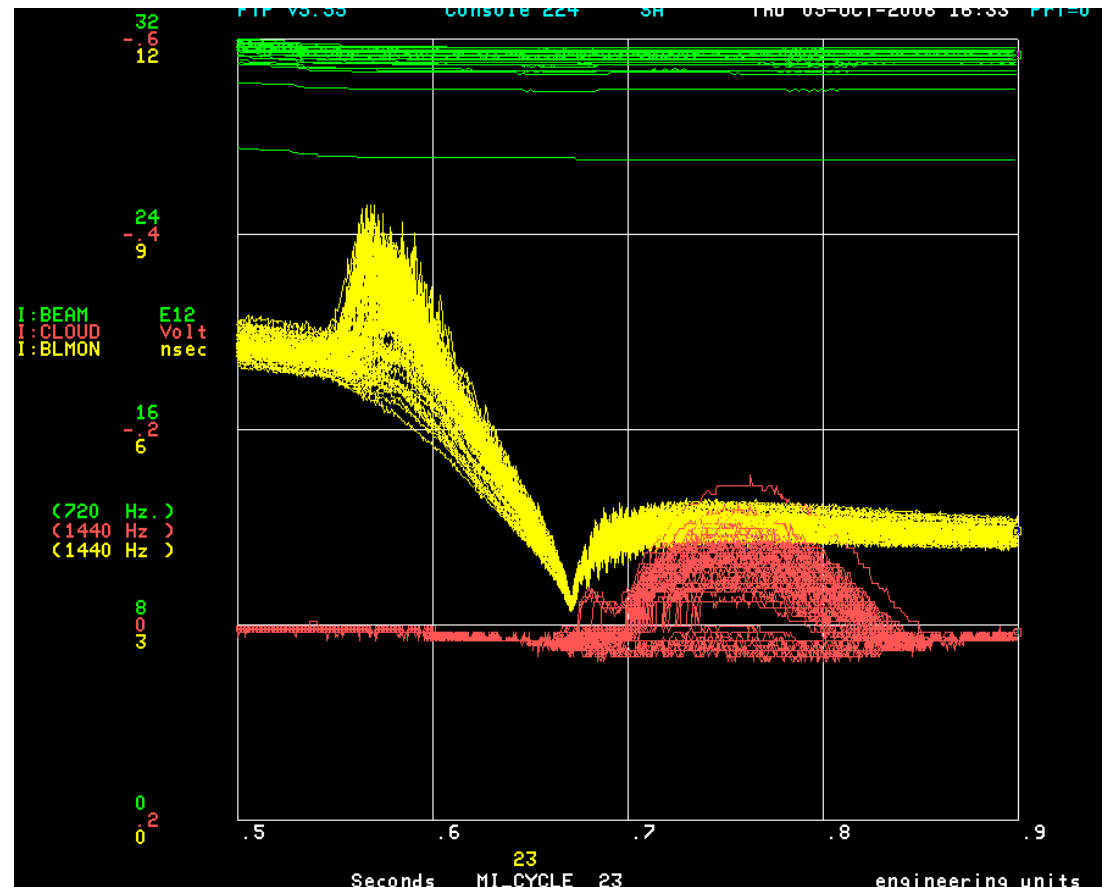
Transition Effect

- Definite decrease in cloud signal at transition
 - Not expected
 - Simulations have suggested that cloud current only increases with smaller bunch length
- Looking into with simulation



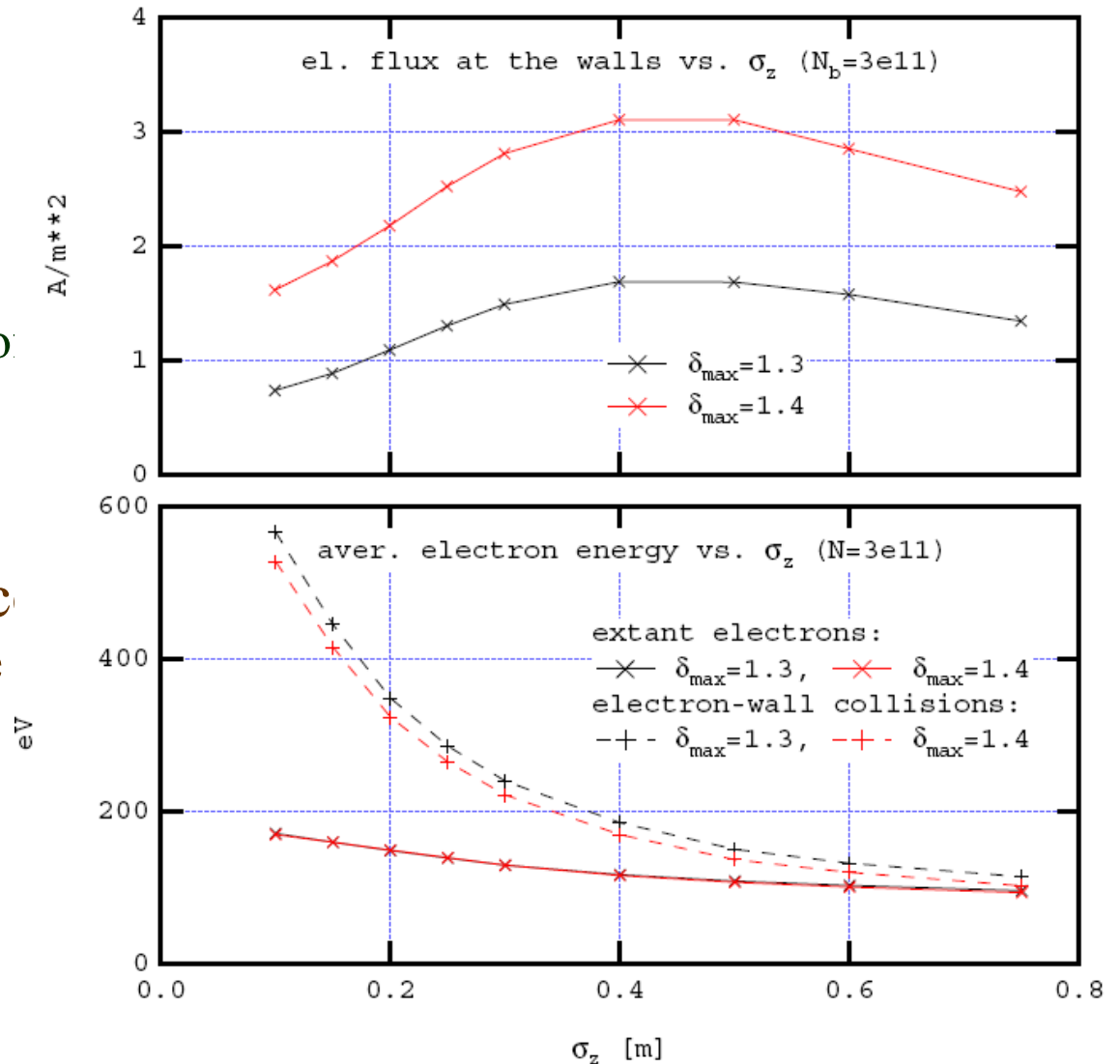
More Transition

- Better filtering/amplifying allow a closer look
 - Introduces time delay
- Some cloud before transition
- Biggest effect after
- Bunch length dependence looks complicated



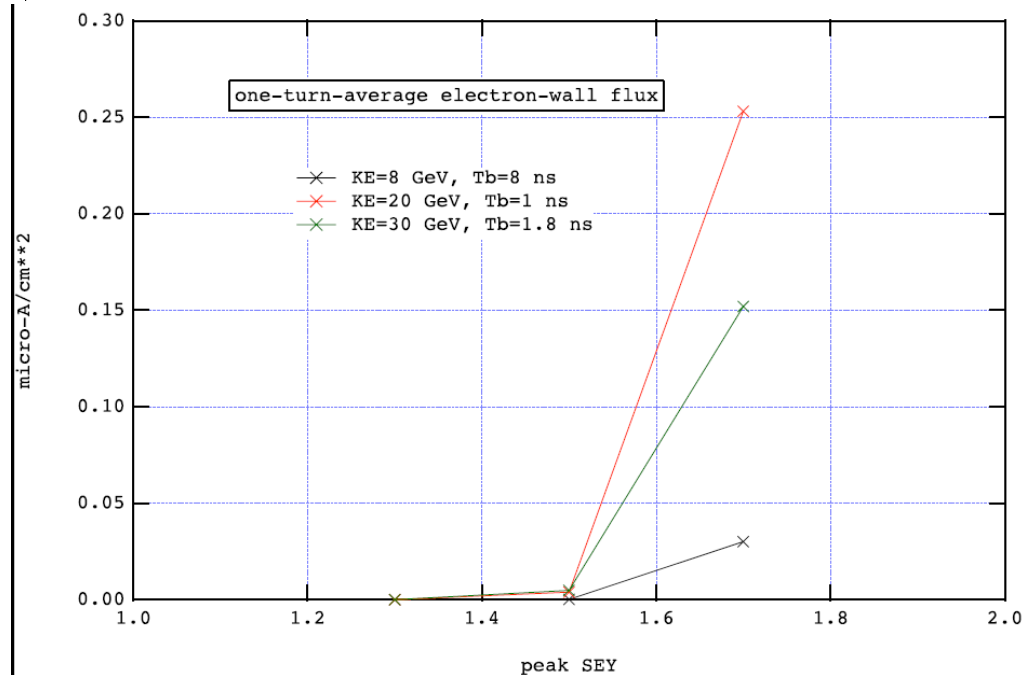
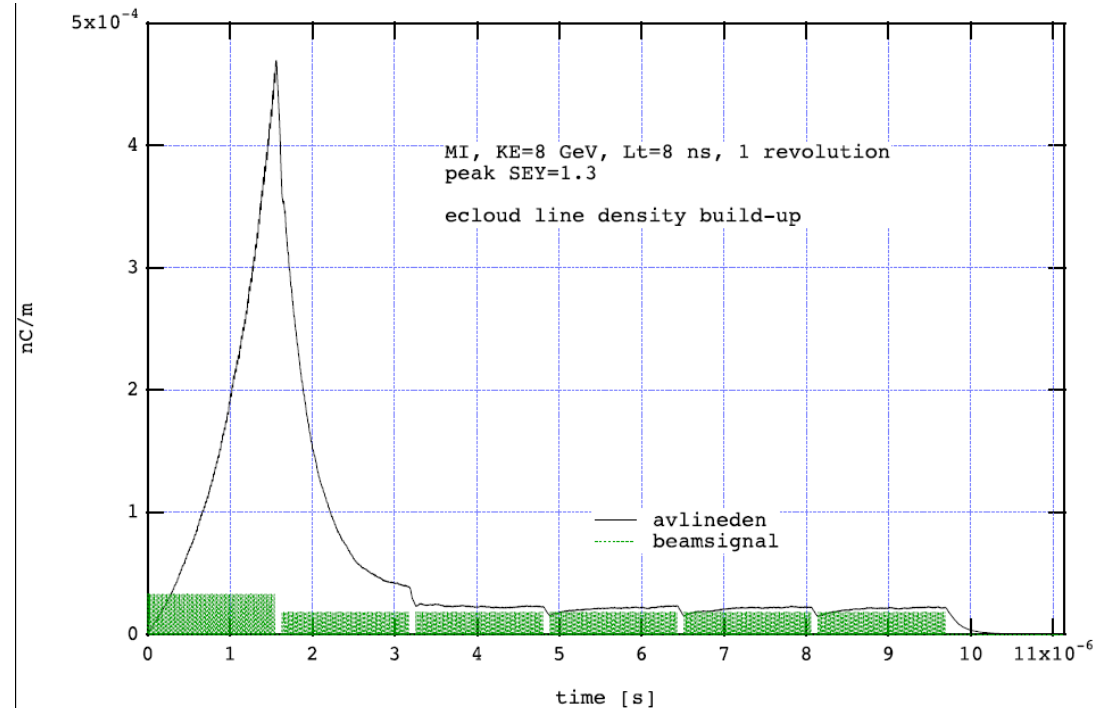
New Simulations

- LBNL now thinks that very short bunches can suppress eccloud in simulation, two causes:
 - Electrons have too high or an energy
 - Too much time between bunches
- However, parameter space is different for MI, so we still don't have a clear correspondence



Simulation Issues

- Secondary emission is a complicated process
 - Measurements suggest our maxes at 1.9-2.0
 - However, simulation saturates well before that level
- Issue with SEY models
 - Multidimensional phase space
 - Electric field at surface



Summary

- The electron cloud is a potentially limiting collective effect in positive particle accelerators
- Fermilab accelerators are not limited by the cloud, but
 - We do observe some cloud activity
 - Simulations suggest that we may be near a threshold
 - Upgrades may double/triple bunch intensities
- Electron cloud under study with observations and simulation
 - Progress has been ongoing, still looking for a clear picture
 - Cloud has been observed in isolated locations
 - Decrease of cloud intensity has been observed at very short bunch lengths
 - May or may not be consistent with simulation
- Consideration of the cloud will be important for any path the Fermilab starts on